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Estimation of walrus populations on sea ice with infrared imagery and aerial photography

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ABSTRACT

Population sizes of ice-associated pinnipeds have often been estimated with visual or photographic aerial surveys, but these methods require relatively slow speeds and low altitudes, limiting the area they can cover. Recent developments in infrared imagery and its integration with digital photography could allow substantially larger areas to be surveyed and more accurate enumeration of individuals, thereby solving major problems with previous survey methods. We conducted a trial survey in April 2003 to estimate the number of Pacific walruses (*Odobenus rosmarus divergens*) hauled out on sea ice around St. Lawrence Island, Alaska. The survey used high altitude infrared imagery to detect groups of walruses on strip transects. Low altitude digital photography was used to determine the number of walruses in a sample of detected groups and calibrate the infrared imagery for estimating the total number of walruses. We propose a survey design incorporating this approach with satellite radio telemetry to estimate the proportion of the population in the water and additional low-level flights to estimate the proportion of the hauled-out population in groups too small to be detected in the infrared imagery. We believe that this approach offers the potential for obtaining reliable population estimates for walruses and other ice-associated pinnipeds.

Key words: aerial survey, Bering Sea, digital photography, infrared, *Odobenus rosmarus divergens*, Pacific walrus, Poisson regression, population estimation, regression estimation, thermal imagery.

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Population sizes of ice-associated pinnipeds are often estimated with visual or photographic aerial surveys (Myers and Bowen 1989, Green *et al.* 1995, Rogers and Bryden 1997, Udevitz *et al.* 2001, Bengtson *et al.* 2005). Aircraft provide one of the best means for covering the vast areas of shifting pack ice where these populations occur (Erickson *et al.* 1993, Green *et al.* 1995). However, the amount of area that can be covered is limited by the relatively slow speeds and low altitudes required for effective photography or visual observation. Photography reduces the potential for observer bias (Thompson and Harwood 1990, Mansfield and St. Aubin 1991), but photographic surveys have generally required animals to be detected visually before they can be photographed. Continuous, unsupervised photography that produces images for both detection and enumeration of individuals has only recently begun to be used in marine mammal surveys (Heide-Jorgensen 2004, Krafft *et al.* 2006).

Continuous images can also be collected by airborne infrared imaging systems (Burn *et al.* 2006). These systems have the potential to allow detection of animals from greater altitudes, increasing the area that can be surveyed per unit time (Dunn *et al.* 2002, Haroldson *et al.* 2003, Bernatas and Nelson 2004). A variety of infrared imaging systems have been investigated, with mixed results, for applicability to surveys of marine and terrestrial species, including cetaceans (Cuyler *et al.* 1992), pinnipeds (Barber *et al.* 1991, Burn *et al.* 2006, Chernook, unpublished data[2]), ungulates (Garner *et al.* 1995, Dunn *et al.* 2002, Haroldson *et al.* 2003), small mammals (Boonstra *et al.* 1994), and birds (Garner *et al.* 1995). Infrared imaging may be particularly effective for walruses (*Odobenus rosmarus*) and ice seals because of their thermal contrast with the ice (Ray and Fay 1968).

Aerial infrared surveys have been used to estimate population sizes for some terrestrial wildlife species, where individuals could be distinguished and enumerated directly from the imagery (Bernatas and Nelson 2004, Kinzel *et al.* 2006). The only example of infrared-based population estimation for a marine mammal we are aware of is for harp seals (*Pagophilus groenlandicus*) in the White Sea (Chernook, unpublished data[2]). In this case, individuals also were enumerated directly from the imagery. Infrared imaging has not been used previously to estimate population size for any species with individuals that could not be separately distinguished within the groups in the imagery.

The Pacific walrus (*Odobenus rosmarus divergens*) population is a significant component of the Bering and Chukchi Sea ecosystems and is an important subsistence resource for coastal communities in Alaska and Chukotka (Fay *et al.* 1997), but the size of this population is unknown (U.S. Fish and Wildlife Service 2002). The U.S. and former Soviet Union made four attempts to jointly estimate this population at 5-yr intervals from 1975 to 1990 (Gilbert 1999, Udevitz *et al.* 2001). However, primarily because of the vast and poorly accessible range of the population, its highly aggregated distribution, and problems with extreme detection and availability biases, none of these efforts provided reliable population estimates (Estes and Gilbert 1978, Hills and Gilbert 1994, Gilbert 1999).

Recent developments in infrared imagery and its integration with digital photography might allow coverage of vast areas and accurate enumeration, solving major problems with previous attempts to estimate walrus populations (Burn *et al.* 2006). Major aggregations of walruses typically occur during spring in association with polynas that form around St. Lawrence Island (Fay 1982). We conducted a trial survey to

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estimate the number of walruses hauled out on sea ice in a portion of this region. The survey used high altitude thermal infrared imagery to detect groups of walruses on strip transects. Individual walruses were not distinguishable within infrared images of densely packed groups. Low altitude digital photography was used to determine the number of walruses in a sample of detected groups and calibrate the infrared imagery for estimating total number of walruses. We used the coefficient of variation (CV) from our trial survey as a basis for a power analysis to estimate the probability of detecting population trends with repeated surveys of this type.

METHODS

Aerial Survey

Our survey area consisted of a 95,000-km^2 region of pack ice in the Bering Sea surrounding St. Lawrence Island (Fig. 1). The area is characterized by a recurring polyna and is known to support major concentrations of walruses during the late winter–early spring breeding season (Fay 1982). The area was partitioned into seven strata designed so that each could be surveyed in a single flight. Due to mechanical problems and lack of additional suitable weather during the survey period, one stratum was not surveyed, and we developed estimates only for the six surveyed strata. Each stratum was partitioned into parallel north–south strip transects. Transects were 6-km wide, corresponding to the field of view for the infrared scanner from our survey altitude. A random sample of transects was selected to be surveyed in each stratum, providing approximately 30% coverage of the stratum area (Fig. 1).

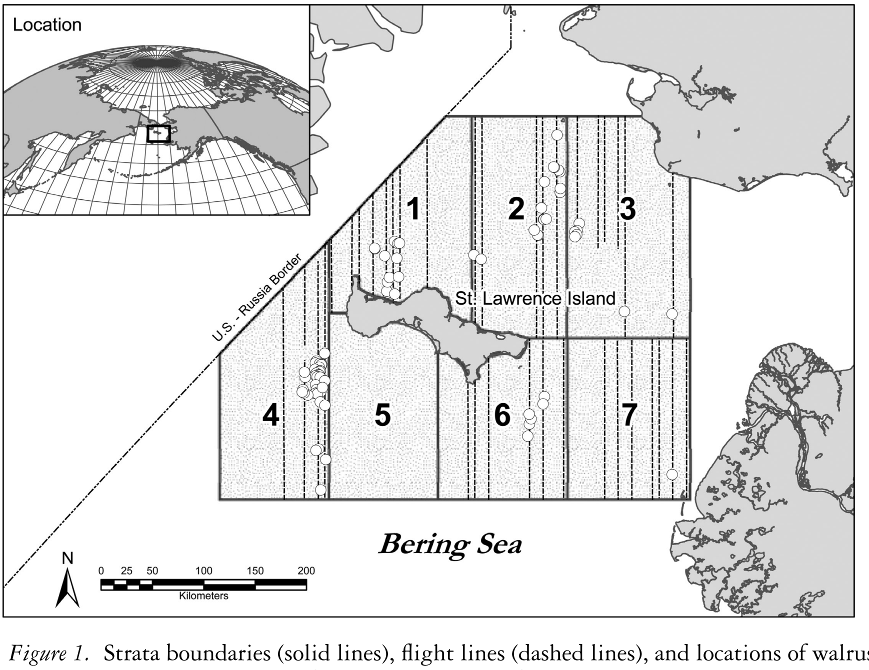

Figure 1. Strata boundaries (solid lines), flight lines (dashed lines), and locations of walrus groups (circles) detected in an infrared aerial survey of sea ice around St. Lawrence Island, Alaska, April 2003.

Surveys were conducted on clear weather days during 5–10 April 2003. We used a Daedelus Airborne Multispectral Scanner, built by SenSyTech, Inc. (now Argon ST) of Ann Arbor, Michigan, and mounted in the tail section of an Aero Commander 690B turbine engine aircraft. The scanner had a 1.25 milliradian instantaneous field of view and collected imagery across a sensor array that was 1,440 pixels wide. We recorded six spectral channels of information, with at least one channel in the thermal infrared (8.5–12.5 μm) range. Each channel was recorded with 12-bit radiometric resolution.

The aircraft flew along the centerline of each selected strip transect at an altitude of 3,200 m and a speed of 370 km/h. At this altitude, the spatial resolution of the infrared imagery was 4 m and the scanner field of view was 6 km. An observer in the aircraft monitored the scanner display during survey operations. Walrus groups were evident as bright spots, contrasting with the darker ice background on the display.

After completing survey transects, the aircraft reduced altitude to 762 m and used GPS coordinates to navigate back to groups detected with the scanner. High-resolution digital photographs were taken of as many of these groups as possible, as well as any other groups in the vicinity, with a 5.47 megapixel, Nikon D1X camera mounted vertically within the aircraft. Photographs were taken with a 180-mm lens that produced an effective ground resolution of 3.4-cm^2 pixels. This resolution was sufficient to distinguish and count individual walruses within a group and was obtained at an altitude that minimized disturbance to resting animals (Burn *et al.* 2006). Each photograph was encoded with latitude and longitude coordinates from a GPS attached to the camera and loaded directly to a notebook computer that was also used to control the camera settings and immediately confirm image quality.

The infrared scanner was also used to detect and record walrus groups while in transit between transects over the study area at the survey altitude. Photographs of these additional groups were obtained opportunistically, with emphasis on larger groups only rarely found on survey transects. Data obtained while not on survey transects were used only for calibrating the infrared imagery and not for estimating abundance.

Data Preparation

Image processing followed procedures developed by Burn *et al.* (2006). Infrared image data were imported directly from 8-mm tape into ERDAS Imagine (Leica Geosystems, Atlanta, GA) software. We examined the temperature histogram of each transect to determine a threshold temperature between walruses and the background environment (Burn *et al.* 2006). Pixels with temperatures warmer than the threshold value were classified as having some portion of their area covered by walruses. We calculated an index of the total amount of heat produced by each walrus group as:

$$h_i = a \sum (t_{ij} - T_i),$$

where h_i was the index for group i, a was the pixel area (m^2), t_{ij} was the temperature for pixel j of group i, T_i was the threshold temperature for the transect containing group i, and the summation was over all pixels with temperature values above the threshold (*i.e.*, pixels with $t_{ij} > T_i$).

To count the number of walruses in the photograph of each group, we used Imagine software and manually marked each walrus with a colored symbol. Each walrus group was enumerated three times by one or more observers on different dates, without reference to previous counts, using a different colored symbol each time. Finally, all three counts were displayed simultaneously and compared to resolve any differences and arrive at a final, rectified count for each group.

We estimated the scanner's detection limit by comparing photographic counts for the smallest thermally detected walrus groups to those for the largest groups that were not thermally detected.

Estimation

Data from all of the photographed groups were used to develop a regression model relating group size to the thermal index. Preliminary examination of the data indicated that variances of the photographic counts were proportional to the mean counts. Therefore, we used a generalized linear model (McCullagh and Nelder 1989) with an identity link and a Poisson distribution to estimate the relation between number of individuals and the thermal index values for the photographed groups. The form of this model was

$$E(y_i) = \alpha + \beta h_i, \, \mathrm{Var}(y_i) = \varphi(\alpha + \beta h_i),$$

where y_i is the number of walruses and h_i is the thermal index for group i, α is the minimum size group that can be detected by the scanner, β is the regression coefficient estimated with maximum likelihood, and ϕ is the dispersion parameter estimated as Pearson's chi-square divided by the degrees of freedom. We assessed model fit using deviance residuals (McCullagh and Nelder 1989, pp. 398–401) and cumulative residuals (Lin *et al.* 2002) and used a likelihood ratio test to assess the regression parameter.

This model was then used to estimate the number of walruses in each group that was thermally detected on a surveyed transect but not photographed. The total number of hauled-out walruses on a surveyed transect was estimated by summing the counts of individuals in all the photographed groups and the estimated counts in all the detected groups that were not photographed on that transect. For transect t in stratum b,

$$\hat{N}_{tb} = \sum_{g=1}^{c_{tb}} y_{gtb} + \sum_{g=c_{tb}+1}^{G_{tb}} (\alpha + \hat{\beta} h_{gtb}),$$

where y_{gtb} is the number of walruses and h_{gtb} is the thermal index for group g on transect t of stratum b. Photographed groups are indexed $1, \ldots, c_{tb}$, and groups that were not photographed are indexed $c_{tb}+1, \ldots, G_{tb}$. If there were no photographed groups on a transect, then $c_{tb} = 0$.

The total population size was estimated as a sum of separate ratio estimators (Thompson 2002) of the totals for each stratum:

$$\hat{N} = \sum_{b=1}^{B} \left(\hat{R}_b \sum_{t=1}^{T_b} A_{tb} \right) = \sum_{b=1}^{B} \hat{N}_b,$$

where

$$\hat{R}_b = \frac{\sum_{t=1}^{t_b} \hat{N}_{tb}}{\sum_{t=1}^{t_b} A_{tb}},$$

A_{tb} is the area of transect t in stratum b, T_b is the number of transects in stratum b, t_b is the number of surveyed transects in stratum b, and B is the number of strata.

We estimated the variance and confidence intervals for the population estimate with a bootstrap procedure based on the general approach of Booth *et al.* (1994) for finite populations. The procedure involved generating a series of simulated populations, estimating statistics of interest by resampling from each simulated population, and then averaging these statistics over the simulated populations.

We generated simulated populations of transects (with associated walrus observations) for each stratum by first replicating the complete set of surveyed transects in the stratum as many times as possible without exceeding the total number of potential transects in the stratum. We then added a random sample without replacement from the surveyed transects to complete the population of potential transects. Bootstrap survey samples were obtained by drawing random samples without replacement from the simulated populations to give the same number of transects as in the original survey.

For each bootstrap survey sample, we also obtained a bootstrap sample of photographic counts for fitting the regression model. A bootstrap sample of photographed groups included all of the photographed groups in the bootstrap sample of surveyed transects if the number of those groups was less than or equal to the number on surveyed transects in the original sample. Otherwise, we sampled without replacement from the photographed groups in the bootstrap sample of transects to obtain the same number as in the original survey. We then completed the bootstrap sample of photographed groups by sampling with replacement from the entire original sample of groups photographed off survey transects to obtain the same total sample size (*i.e.*, number of groups photographed on transects + number of groups photographed off transects) as in the original survey. This resampling strategy was designed to approximate the survey protocol, which supplemented the essentially random distribution of group sizes photographed on survey transects with additional off-transect photographs emphasizing larger groups, thereby obtaining a more even distribution of group sizes for the calibration regression.

Estimation for each bootstrap sample followed the same procedure as for the original sample. We obtained 100 bootstrap samples and associated estimates of population size for each simulated population and then calculated the standard error and 2.5 and 97.5 percentiles of those estimates. We repeated this process for 500 simulated populations and took the average of the standard errors and 2.5 and 97.5 percentiles as our estimates of standard errors and 95% confidence limits (Manley 1991) for the estimates from the original survey. We checked for convergence of estimates to ensure the number of bootstrap samples and simulated populations were sufficient.

Power Analysis

We used the estimated CV from our trial survey as a basis for conducting a power analysis with TRENDS software, available at http://swfsc.noaa.gov/prd.aspx

(Gerrodette 1987, 1991). For comparison to previous surveys, we also considered CV values ranging up to 0.60, which was the value estimated by Hills and Gilbert (1994) for the joint Russian–American surveys of the Pacific walrus population conducted from 1975 to 1990. Following Taylor *et al.* (2007), we estimated the probability of detecting a "precipitous decline" in the population, which they defined as an exponential decline of 5% per year over a 15-yr period. Detection of trend was based on a t-test of the slope parameter in a linear regression of estimated population size versus time. We considered three different monitoring schedules, requiring surveys to be conducted at either 5-yr intervals (an initial survey plus three additional surveys), 3-yr intervals (an initial survey plus four additional surveys), or annually (an initial survey plus 15 additional surveys). The 5-yr interval matched the schedule of joint Russian–American surveys of the Pacific walrus population (Gilbert 1999, Udevitz *et al.* 2001). Also following Taylor *et al.* (2007), we assumed that the CV was proportional to 1/sqrt(population size), used a one-tailed test of significance, and required the customary significance level of $\alpha = 0.05$. However, this significance level may be unduly conservative, giving too much emphasis to guarding against type I (overprotection) errors and too little emphasis to guarding against type II (under protection) errors (Taylor *et al.* 2007). Therefore, we also estimated the CV that would be required to obtain a power of 0.9 with $\alpha = 0.10$ and a power of 0.8 with $\alpha = 0.20$, which balance the probabilities of over- and under protection errors.

RESULTS

We obtained photographs of twenty-five groups of walruses, ranging in size from 4 to 315 individuals, that were also detected with the scanner (Fig. 2). Of these, ten groups were detected on surveyed transects; fifteen groups were detected while in transit over the study area. An additional six groups, ranging in size from one to four individuals, were photographed but could not be detected in the corresponding

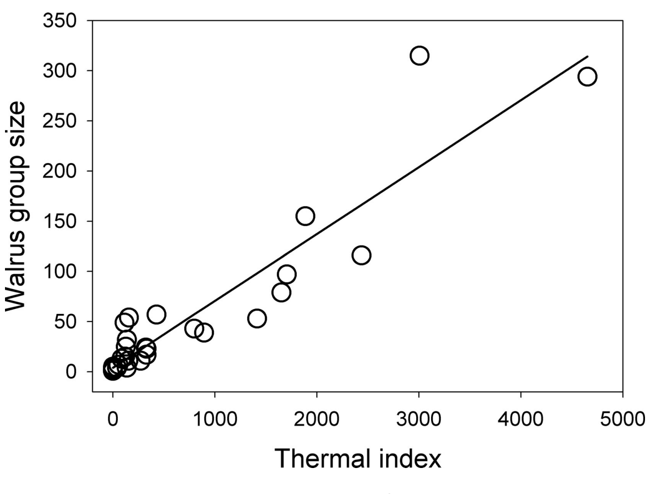

Figure 2. Group sizes and thermal index values of walrus groups photographed on sea ice around St. Lawrence Island, Alaska, April 2003. Solid line is a Poisson regression model fit to these data and used to calibrate the infrared scanner.

Table 1. Areas of strata, proportions of areas covered, and walrus groups detected in an infrared aerial survey of sea ice around St. Lawrence Island, Alaska, April 2003.

Stratum	Total area (km^2)	Proportion of area surveyed	Number of detected groups	Estimated number of individuals per detected group	
				Mean	Range
1	13,808	0.31	15	9	4–28
2	15,903	0.35	20	36	4–259
3	18,455	0.25	8	16	5–42
4	17,525	0.21	41	7	4–26
6	15,310	0.30	7	22	4–54
7	15,900	0.38	1	4	4

infrared images (Fig. 2). The smallest photographed groups that were detected in the infrared imagery contained four walruses (two groups). We therefore assumed that the groups of less than four walruses were not detectable (*i.e.*, $\alpha = 4$).

There was a strong linear relationship ($\chi^2_1 = 90.02, P < 0.01$) between the number of walruses in a group and the thermal index (Fig. 2), with a slope parameter estimate of $\beta = 0.067$ (SE $= 0.0070$). Plots of deviance residuals showed no lack of fit to the linear model or the Poisson variance function. For comparison, a Poisson regression without the assumed detection limit gave very similar estimates of $\alpha = 5.94$ (SE $=$ 2.96) and $\beta = 0.065$ (SE $= 0.0074$).

We surveyed thirty-five transects in six strata, covering 30% of the total area of those strata with the scanner (Table 1). A total of 92 walrus groups were detected on surveyed transects, with estimated number of individuals ranging from 4 to 259 per group (Table 1). This gave a total estimate of 4,784 (CV $= 0.25$) hauled-out walruses in the six surveyed strata at the time of the survey (Table 2).

Assuming a CV of 0.25 for the population estimate from each survey and requiring a significance level of $\alpha = 0.05$ to test for trend, we estimated that the probability of detecting a precipitous decline in the population would be 0.36 if surveys were conducted every 5 yr, 0.54 if surveys were conducted every 3 yr, and 0.91 if surveys were conducted annually (Fig. 3). In all of these cases with $\alpha = 0.05$, the probability of a type I error (overprotection) was greater than the probability of a type II error (under protection). A probability of 0.80 for detecting a precipitous decline could be obtained with surveys conducted at 5-yr intervals if the significance criteria for

Table 2. Estimated number of walruses hauled out on sea ice in survey strata around St. Lawrence Island, Alaska, April 2003.

Stratum	Total walruses	Standard error (SE)	95% confidence interval
1	424	166	131–761
2	2,057	846	395–3,693
3	509	349	40–1,252
4	1,278	509	555–2,259
6	505	317	3–1,050
7	12	9	0–29
Total	4,784	1,186	2,499–7,111

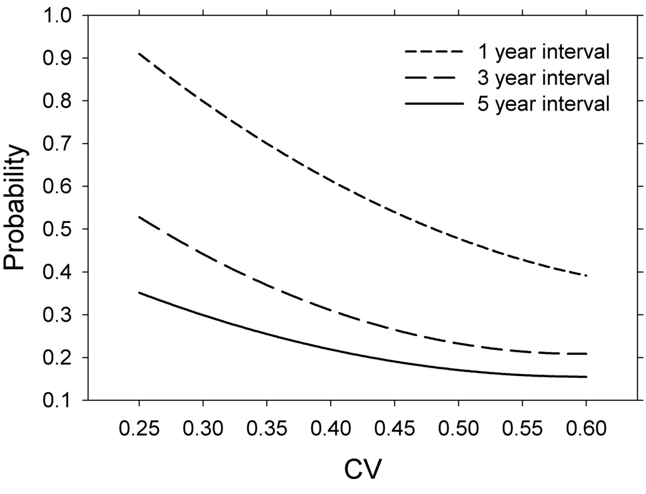

Figure 3. Probability of detecting a precipitous population decline (Taylor *et al*. 2007) with repeated surveys conducted at intervals from 1 to 5 yr, a significance level of $\alpha = 0.05$, and a range of CV values for population estimates from individual surveys.

the *t*-test was increased to $\alpha = 0.20$ (Table 3). This would balance the probabilities of over- and under protection errors. Using the CV of 0.60 estimated by Hills and Gilbert (1994) for the joint Russian–American surveys and requiring $\alpha = 0.05$, gave an estimated probability of 0.15 for detecting a precipitous decline with surveys conducted at 5-yr intervals (Fig. 3).

Discussion

Our work provides the first published estimate of a walrus population based on an infrared survey. Our approach addresses the major problems of limited coverage and inaccurate enumeration identified by Gilbert (1999) in previous visual surveys of walruses. Use of an infrared scanner flown at relatively high altitude allows detection of walrus groups over a substantially larger area than was possible with previous visual surveys. Use of low-level photography to calibrate the infrared imagery allows

Table 3. Minimum CVs for population estimates required to detect precipitous population declines (Taylor *et al*. 2007) with repeated surveys conducted at intervals from 1 to 5 yr and balanced probabilities of overprotection (α) and under protection (β) errors.

		Interval between surveys (yr)		
$\alpha = \beta$	$1 - \beta$	1	3	5
0.10	0.90	0.30	0.18	0.14
0.20	0.80	0.49	0.30	0.25

The probability of detecting a precipitous decline is $1 - \beta$.

relatively precise estimation of the number of walruses in the detected groups (Barber *et al*. 1991, Burn *et al*. 2006).

Although the region around St. Lawrence Island has long been recognized as an important spring aggregation area for Pacific walruses (Fay 1982), our trial survey provides the first quantitative estimate of the number of walruses in a portion of this region. Our estimate is a minimum value however because we did not account for (1) walruses that were in the water and therefore unavailable to be detected by the scanner, (2) walruses hauled out in groups too small to be detected (*i.e.*, group size < four), and (3) walruses in the unsurveyed stratum (stratum 5, Fig. 1). As is typical for aerial surveys, we assumed there was no net movement of individuals among strata during the survey period or among transects during any survey day.

Stratum 5 was not surveyed due to a mechanical problem with the scanner on the last remaining day with suitable weather during the survey period. Our survey method requires mostly clear skies because infrared radiation does not penetrate clouds. Weather conditions were suitable for surveying at the designated altitude on only 7 of the 14 d allotted for our trial survey. Thus, the requirement for cloud-free skies constitutes an important limitation to the application of this approach. Flying at a lower altitude can circumvent the problem of high clouds, but this will reduce the area that can be covered.

We had very few photographs of groups that were undetected by the scanner on surveyed transects. However, analysis of these photographs indicated that the detection limit for our scanner was essentially the same as that observed in an earlier pilot study conducted by Burn *et al*. (2006) under similar conditions. Based on this consistency of results and our lack of sufficient data for more rigorous estimation of the detection limit and its precision, we treated the apparent detection limit as a known constant in our analyses. Ideally, the uncertainty in the estimated detection limit should be accounted for along with the other sources of uncertainty affecting the population estimate. Reliable estimation of the detection limit will require additional data on undetected groups that could be obtained with low-level photography. Low-level photography would be accomplished most efficiently with a second dedicated aircraft. Recent evidence (USFWS unpublished data) suggests that the detection limit may depend on ambient temperature and wind speed. These variables could be used as covariates in the regression model relating the thermal index to group size.

The total number of walruses that were hauled out but undetectable in our survey because they occurred in groups of less than four individuals is likely to be relatively small. This is because walruses tend to aggregate in large groups on sea ice (Fay 1982), and individuals in small groups account for a very small portion of the hauled-out population (Estes and Gilbert 1978). Nevertheless, in a full population survey, it would be desirable to estimate the size of the undetectable portion of the hauled-out population. This could be accomplished with a low level visual-photographic line transect survey conducted on a subset of the transects covered by the scanner. The estimated size of this portion of the population could then be added to the total for the rest of the population. The precision of the estimate for this undetectable portion of the population is likely to be low because of the limited sample size that can be obtained with a low level survey. However, the effect on the precision of the overall estimate is likely to be small because the portion of the population accounted for by undetected groups is also likely to be small. An advantage of a resolution that does not detect the smallest groups of walruses is that ice seals are also likely to be in groups that are too small to be detected and therefore will not inflate walrus population estimates.

Our survey design was similar to stratified double sampling for regression estimation (Thompson 2002), but there were not enough walrus groups photographed in secondary samples on transects to support sufficiently precise regression estimates within transects or strata. Therefore, walrus groups detected with the infrared scanner while in transit between survey transects were also photographed and data from all photographed groups were pooled to develop a common regression model for all strata. When a common model is estimated from data taken in different strata, the strata estimates are correlated, and this requires special consideration in estimating variances (Bowden *et al.* 2003). Our bootstrap approach for estimating standard errors and confidence intervals accounted for this correlation as well as the other aspects of the survey design.

Minimizing the time between infrared scanning and digitally photographing walrus groups can reduce variances of calibration estimates. In some cases, up to an hour elapsed between the times when the two images of a group were obtained because the aircraft had to reduce altitude and return to photograph groups after completing the high altitude scan of a transect. Although we have no reason to suspect any bias, sizes of some groups may have changed during this interval, increasing the variability associated with the calibration regression. Use of a second aircraft dedicated to photography could reduce the intervals between image acquisitions.

Estimating the total number of walruses in a region would require additional information about the proportion of the population that was not hauled out on the ice and therefore not available to be detected by the infrared scanner. Data for estimating this proportion could be obtained from a sample of walruses fitted with satellite transmitters containing sensors that measure the proportion of time a walrus is in the water (Hills and Gilbert 1994). This type of transmitter along with a technique for remotely deploying relatively large numbers of them has been developed recently (Jay *et al.* 2006). A Horvitz–Thompson type estimator (Thompson 2002) could be used to adjust the total estimate to account for the proportion of the population available to be detected.

Hills and Gilbert (1994) estimated that using sample of thirty instrumented walruses to adjust for the proportion of the population in the water would add 0.02–0.07 to a CV of 0.25 for the estimate of the hauled-out population. Thus, it might be reasonable to assume that a CV of around 0.27–0.32 could be achieved for a total estimate of the Pacific walrus population using the new survey technology. Estimates of the Pacific walrus population size are required to set conservation policy in Russia and for compliance with the Marine Mammal Protection Act in the United States, but estimates of population trend will also be required for the most effective management of this population (Hills and Gilbert 1994). With $\alpha = 0.05$, the probability of detecting a precipitous decline with the new survey technology would probably still be unacceptably low, unless surveys could be conducted annually (Fig. 3). With $\alpha = 0.2$, however, a more reasonable probability of about 0.8 for detecting a precipitous decline could be obtained with intersurvey intervals of 3–5 yr (Table 3). In any case, this would represent a substantial improvement over the ability to detect trends with the technology used in previous walrus surveys (Hills and Gilbert 1994) or in other surveys of pinnipeds on sea ice (Taylor *et al.* 2007). The CV could be reduced further by surveying more transects or by using an infrared scanner with a smaller instantaneous field of view and correspondingly larger pixel array.

Gilbert (1999) suggested that a spring survey of the Pacific walrus population could be effective because the entire population is distributed near the edges of the Bering Sea ice pack at that time. We propose a design for a spring survey that includes four major components: (1) deployment of satellite transmitters on a representative sample of walruses to estimate the proportion of the population hauled out on ice during the survey, (2) a high altitude strip transect survey using an infrared scanner to detect groups of hauled-out walruses, (3) low altitude digital photography of a sample of walrus groups within the surveyed transects to estimate number of walruses in groups detected with the scanner, and (4) a low altitude visual-photographic line transect survey along a subsample of transects covered by the scanner to estimate the number of hauled-out walruses in groups too small to be detected by the scanner and to aid in estimating the scanner detection limit. Components (3) and (4) could both be accomplished by a single aircraft dedicated to low-level photography. The technology required for this approach is now available, and our trial survey has demonstrated that the key elements of the design are operationally feasible. We believe that this approach offers the potential for obtaining the most reliable estimate to date of the Pacific walrus population size. These technologies may also prove useful for estimating populations of other ice-associated pinnipeds.

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